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INTEGRATED PROCESSING OF PRIMARY TITANOMAGNETITE ORES OF UKRAINE WITH RECOVERY OF VANADIUM-BEARING CONCENTRATE

Abstract. The study investigates the mineral composition, technological properties, and potential for the integrated utilisation of primary titanomagnetite ores of Ukraine with the aim of producing a vanadium-bearing concentrate.

The studies were conducted in laboratory conditions according to standard methods using magnetic separators of roller type 138T-SEM and rotary type 259-SE; concentration table SKM-2.

During the research, the material composition and technological properties of the ore were studied, on the basis of which a technological enrichment scheme was developed.

It is established that the principal ore minerals are titanomagnetite (13.5%), ilmenite (≈5%), and apatite (6.08%), while the gangue is mainly represented by plagioclase, pyroxenes, and olivine. Vanadium predominantly occurs isomorphically within the titanomagnetite structure, which complicates its extraction.

For the first time, for primary titanomagnetite ores of Ukraine, the feasibility of recovering a vanadium-bearing concentrate at the initial stage of beneficiation is substantiated. This approach enhances process selectivity and reduces resource consumption. Scientific approaches to combined magnetic–gravity beneficiation is further developed, taking into account the degree of mineral liberation and their physical properties.

Based on mineralogical and granulometric studies, it is determined that complete liberation of ore minerals is achieved at a particle size of −0.074 mm. Magnetic analysis showed that titanomagnetite is efficiently recovered over a wide range of magnetic field intensities; however, increasing field strength leads to greater entrainment of associated silicate minerals.

The effectiveness of both dry and wet magnetic separation is experimentally confirmed. A titanomagnetite concentrate was obtained with a yield of 13.6%–13.9% and containing 22.0%–22.3% TiO_2, up to 53.1% Fe, and up to 0.51% of V_2O_5. Subsequent gravity beneficiation enables an increase in TiO_2 content to 24.1%–36.16%, depending on the feed type.

The practical significance of the study lies in the development of an efficient processing flowsheet that ensures the integrated utilisation of raw materials, reduces water and energy consumption, and can be implemented in the design of mineral processing plants, as well as in the development of the raw material base for titanium, iron, and vanadium in Ukraine.

Keywords: titanomagnetite ores; integrated beneficiation; vanadium; processing flowsheet.

1. Introduction

The operational experience of industrial enterprises demonstrated that production economics depends on the manner in which raw materials are utilised. This involves the rational selection of raw materials and their integrated processing, ensuring highly efficient primary treatment and beneficiation of minerals with minimisation of resource losses, as well as the implementation of sustainable development and circular economy principles through reuse of products and maximum involvement of production waste in economic circulation.

The selection of raw materials determines the type of technological equipment, the nature of the process, the duration of the production cycle, and influences numerous technical and economic performance indicators of the enterprise. All raw materials of mineral and organic origin contain a range of valuable components. The completeness of their recovery and utilisation depends on demand and the level of technological development.

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Comprehensive utilisation of raw materials increases production efficiency, ensures expansion of product volume and assortment, reduces production costs and expenditures on raw material base formation, and prevents environmental pollution by industrial waste. Therefore, this principle is always required in the development of new deposits.

Titanomagnetite deposits, which serves as carriers of titanium and iron in primary ilmenite ores, are not an exception. These ores contains vanadium, which, during beneficiation, is concentrated in the titanomagnetite fraction in significant quantities, thereby increasing the industrial value of this mineral.

Such ores are not developed in Ukraine. However, several deposits of primary ilmenite ores are available, the development of which could replenish the raw material base of iron, titanium, and vanadium. Therefore, in the development of ore beneficiation technologies, the investigation of the technological properties of titanomagnetite are considered one of the key tasks for enhancing the comprehensiveness of deposit utilisation.

At beneficiation plants processing titanomagnetite ores, particularly at Otanmäki Mine (Finland), combined technological schemes are applied, including crushing, grinding, dry and wet magnetic separation, followed by ilmenite flotation and processing of magnetite concentrate for vanadium recovery [1].

In contrast, at Titania AS (Tellnes Mine, Norway), which exploits high-grade ilmenite ores, the beneficiation process is primarily based on gravitational and magnetic methods and is less complex [2]. Similar approaches to magnetic extraction of magnetite are also applied at classical enterprises within EU countries, where the main objective is to obtain iron ore concentrate with minimal titanium content [3].

Modern studies confirms the efficiency of combining gravitational and magnetic beneficiation (spiral separators, shaking tables, high-gradient magnetic separation) [4]. In particular, in the Panxi–Sichuan region (China), multistage schemes are applied, including low- and high-gradient magnetic separation followed by ilmenite recovery [5, 6, 7].

In deposits of the Bushveld Complex (South Africa), magnetic beneficiation followed by pyrometallurgical processing is the primary method, due to the complex mineralogy of the ores [8]. For ilmenite sands (Richards Bay, South Africa), a combination of gravitational and magnetic methods is characteristic, ensuring high selectivity of the process [9].

Vanadium in titanomagnetite ores generally enters the crystal lattice of magnetite (Fe_3O_4) isomorphically, partially substituting Fe^{3+}. This results in difficulties in its extraction, as it does not form independent mineral phases.

The main technological task consists in converting vanadium into a water-soluble form (most commonly sodium or calcium vanadates), followed by its recovery.

Modern studies demonstrates that the principal industrial method for vanadium extraction from titanomagnetite remains oxidative soda roasting at 750–900 °C with sodium reagent consumption of 5–20%, ensuring recovery of up to 90% [10].

At the same time, low-temperature technologies are actively developed, including roasting with NaOH at 400–500 °C with recovery up to 96.6% [11], as well as combined "roasting–leaching" schemes enabling recovery exceeding 90% [12].

Environmentally oriented approaches are considered promising, particularly the use of deep eutectic solvents, which ensure vanadium recovery up to 97% at temperatures of approximately 100 °C [13].

Comparative characteristics of methods for extracting vanadium from titanomagnetites are given in Table 1.

Table 1 – Characteristics of methods for vanadium extraction from titanomagnetites

Method	Temperature	Reagents	V recovery	Features
Oxidative roasting	900–1000 °C	Na_2CO_3, CaO	80–90%	The most widely used method
Alkaline leaching	80–150 °C	NaOH, Na_2CO_3	60–85%	Lower impurity levels
Acid leaching	60–120 °C	H_2SO_4	50–75%	Iron dissolution occurs
Combined method	900 °C ± 100 °C	$Na_2CO_3 + H_2O$	85–92%	Optimal vanadium recovery
Chloride method	600–900 °C	Cl_2	70–85%	Complex and toxic process

The aim of the study consisted in the development of a technology for obtaining concentrate from complex primary titanomagnetite ores of Ukraine based on the identification of mineralogical and chemical composition features and the establishment of patterns of magnetic and gravitational separation of titanomagnetite with recovery of vanadium-containing concentrate.

To achieve this aim, the following tasks were addressed:

– investigation of the material composition of ore samples;

– study of magnetic properties of minerals;

– laboratory investigations;

– development of beneficiation technology.

2. Methods

A technological sample of titanomagnetite ore with a mass of 300 kg was taken for technological studies aimed at developing a beneficiation flowsheet.

The investigations were carried out under laboratory conditions.

The material composition and technological properties of the ore was studied, based on which a beneficiation flowsheet was developed.

The mineral composition of the initial ore was examined macroscopically and microscopically in transmitted and reflected light. Quantitative estimation of minerals was performed using an ISA-3 integrating table [14].

Granulometric characteristics were preliminarily assessed using an eyepiece micrometer, allowing determination of the particle size class with maximum grain liberation.

A mineralogical analysis was performed on the classified crushed material of the initial sample. From each size fraction, secondary subsamples were obtained by quartering, each comprising an average of 314 fragments. The material was divided into two categories: free particles and intergrowths. Among the latter, four groups were distinguished [14]:

– intergrowths composed of more than 75% of a single mineral;
– intergrowths composed of 50–75% of a single mineral;
– intergrowths containing 25–50% of a single mineral;
– intergrowths containing up to 25% of a single mineral.

Following recalculation to a free particle basis, the mineral content in each fraction was determined. The ratio of free particles to intergrowths across size classes provided a more accurate assessment of the degree of grain liberation after crushing.

Magnetic analysis was conducted using a magnetic analyser and an electromagnetic roll separator, with gradual increase in magnetic field intensity from 80 kA/m to 960 kA/m [15].

Laboratory-scale investigations of high-intensity magnetic separation were carried out using a rotary-type separator 259-SE. The feed material, containing 70% of the −0.074 mm size fraction with a solids mass fraction of 30%, was loaded to the working zone of the separator, consisting of riffled plates with a height of 200 mm. The matrix loading was 0.2 g/cm³.

The separator was equipped with a scavenging rotor with magnetic induction three times lower than that of the axial rotors. The scavenging rotor removed part of the magnetic product from the plates of the main rotors, which resulted in increased recovery of titanium-bearing particles into the magnetic product.

High-intensity magnetic separation was performed using a rotor-type separator. Magnetic induction varied from 0.6 to 1.2 T [15].

Gravitational beneficiation was carried out on an SKM-2 shaking table with a feed rate of 15–20 kg/h at varying particle sizes of the feed material. The inclination angle of the table deck varied from 2^0 to 10°, the stroke length - from 10 mm to 16 mm, and the oscillation frequency from 4 Hz to 7 Hz.

Evaluation of the results of technological investigations was performed through the chemical and mineralogical analyses of the beneficiation products.

Gravitational beneficiation was carried out on a shaking table under varying operational parameters.

3. Results and discussion

The chemical and mineral compositions of primary titanomagnetite ore was investigated using a laboratory technological sample.

The ore was represented by crystalline rocks (gabbro, gabbro-peridotite, peridotite) containing apatite, ilmenite, and titanomagnetite disseminations.

The average content of TiO_2 was 6.59%, and of P_2O_5 was 2.36%.

The results of the chemical analysis of the titanomagnetite ore indicated that the principal petrochemical components were SiO_2 (34.0), Fe_2O_3, (22.4), FeO (22.4), CaO (10.42), Al_2O_3 (8.0), TiO_2 (6.35), and Na_2O (1.27); secondary components included MgO (6.3) and P_2O_5 (2.49); accessory components comprised MnO, K_2O, CuO, ZnO, and BaO, each with a content not exceeding 1.0%. The rock was characterised by a high content of rock-forming components, namely SiO_2, Al_2O_3, CaO, and MgO.

The principal and secondary components were concentrated in the main minerals of the investigated ores: plagioclase (SiO_2, Al_2O_3, CaO, Na_2O), pyroxene (FeO, MgO, SiO_2), olivine (FeO, MgO, SiO_2), titanomagnetite (FeO, Fe_2O_3, TiO_2), ilmenite (FeO, TiO_2), apatite (CaO, P_2O_5), and pyrrhotite (FeO, SO_3). The presence of other components was attributed to their impurity nature - MnO - in pyroxene; K_2O and BaO in plagioclase; or to the low content of the mineral in which the component was mineral-forming (CuO in chalcopyrite). The presence of ZnO was most likely explained by the isomorphism of zinc and iron in chalcopyrite or by the occurrence of trace amounts of sphalerite not detected in the polished sections.

It was established that 87.19% of TiO_2 was associated with ilmenite and titanomagnetite, while 94.46% of P_2O_5 was associated with apatite.

The mineral composition of the ore (Table 2) was determined by the content of minerals of industrial interest, on the one hand, and rock-forming minerals, on the other. The former included ilmenite, titanomagnetite, and apatite; the latter comprised various silicates, predominantly represented by plagioclase, pyroxene, and olivine.

Table 2 – Mineral composition of the ore

Mineral phase	Mass fraction, %
Titanomagnetite	13.5
Ilmenite	5.1
Apatite	6.08
Iron sulphides	0.67
Iron hydroxides	0.5
Plagioclase	28.6
Olivine and pyroxenes	45.55
Total	100

A petrographic characterisation of the principal ore minerals of the investigated ore is presented below.

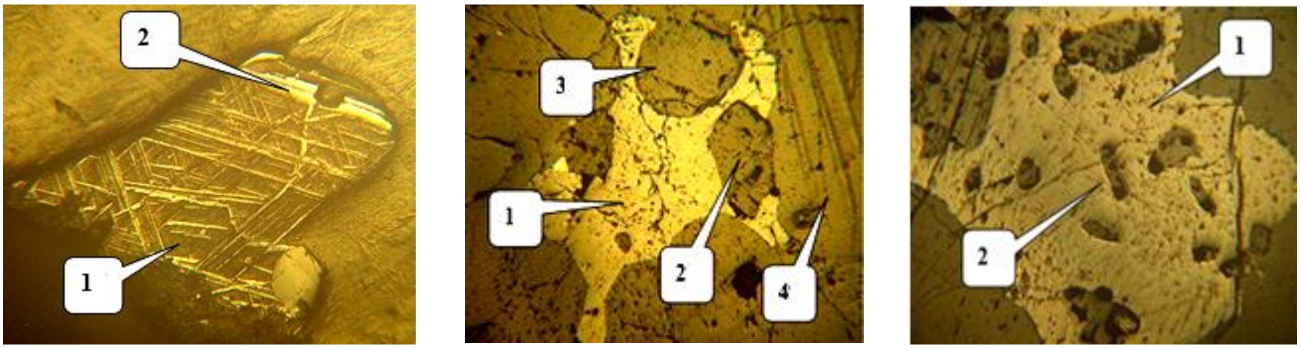
Magnetite is identified as one of the main ore minerals. Its content in gabbro ranges from 3.9 to 18.9% (on average 9.8%), in peridotites from 18.5 to 26.2% (22.4%), and in gabbro-peridotites from 13.3 to 17.0% (14.9%). Two varieties are distinguished: magnetite proper and titanomagnetite, the latter representing magnetite with ilmenite exsolutions (solid solution decomposition structures).

Magnetite forms xenomorphic aggregates, and occasionally fine spherulite-like grains, whereas titanomagnetite is represented by hypidiomorphic grains and their aggregates. Grain size varies from 0.001 mm to 1.7 mm (on average 0.8 mm).

Magnetite is closely associated with ilmenite, forming both exsolution structures and complex intergrowths with silicates (plagioclase, pyroxene, olivine) and sulphides. Fracturing and partial dissolution of minerals are observed.

Titanomagnetite is identified as the dominant ore mineral (13.5%), characterised by a complex internal structure (Fig.1).

The principal constituents are magnetite and ilmenite, with magnetite forming a matrix in which lamellar ilmenite precipitates (up to 0.01 mm) are distributed, often oriented so as to form lattice-like structures. Ilmenite inclusions of partially melted morphology, up to 0.1 mm in size, are also observed. The TiO_2 content in titanomagnetite can reach up to 25%.



a b c

(a) exsolved titanomagnetite grain (1) with more stable lamellar ilmenite intergrowths (2); (b) xenomorphic titanomagnetite (1) filling the space between grains of apatite (2), olivine (3) and plagioclase (4); (c) xenomorphic titanomagnetite (1) with fine inclusions of apatite (2)

Figure 1 – Morphological features of titanomagnetite from primary deposits. Reflected light

Ilmenite is present in the ore in an amount of approximately 5.1%. It is predominantly represented by rounded or slightly elongated grains ranging from 0.06 to 0.7 mm in size, frequently intergrown with titanomagnetite to form complex aggregates. A portion of ilmenite is incorporated into the structure of titanomagnetite.

Mineral liberation studies showed that in coarse size fractions (–5.0 + 2.0 mm), the material is entirely represented by intergrowths, predominantly of silicates with ore minerals. With decreasing particle size, the proportion of grains is increased, and complete liberation is achieved in the size fraction –0.16 + 0.071 mm.

It is established that the ore minerals are characterised by different values of density, as well as electrical and magnetic properties, which substantiated the feasibility of applying gravitational, electrical, and magnetic beneficiation methods.

A generalisation of the results showed that titanomagnetite is the principal ore mineral (13.5%), while ilmenite (≈4–5%), apatite (6.7%), and sulphides (2.7%) are of secondary importance. Mineral dissemination is uniform.

The mass fractions of Fe_{total}, TiO_2, P_2O_5, and V_2O_5 in the ore are 21.2%, 6.35%, 2.49%, and 0.115%, respectively. The grain size of titanomagnetite ranges from 0.001 mm to 1.7 mm; complete liberation requires grinding to 0.074 mm followed by the application of combined beneficiation methods.

Magnetic analysis of ore from one of the primary deposits of Ukraine showed that, irrespective of particle size class, the distribution of minerals across magnetic fractions is identical. At magnetic field intensities of 55.7–79.6 kA/m, ilmenite, in addition to titanomagnetite, is recovered into the magnetic product in the form of intergrowths with dark-coloured minerals and plagioclase, as well as sulphides. With increasing magnetic field intensity, the proportion of dark-coloured minerals in the magnetic product is continuously increased.

At 644.9–899.7 kA/m, virtually all ilmenite, olivine, pyroxene, and their intergrowths are recovered into the magnetic product. Olivine and ilmenite are concentrated in the magnetic fraction at a field intensity of 644.9 kA/m. Pyroxenes are observed in all fractions; however, their maximum recovery is recorded at 640–899.7 kA/m. Ilmenite grains are almost absent in the non-magnetic product.

Apatite and plagioclase are predominantly concentrated in the non-magnetic product and, to a lesser extent, in the magnetic fraction at a field intensity of 899.7 kA/m. Apatite grains are recovered into the magnetic product due to the presence of very fine ilmenite inclusions within titanomagnetite. The non-magnetic product is consisted of 96–98% plagioclase, apatite, and their intergrowths.

Within the investigated particle size ranges, a uniform distribution of P_2O_5 in magnetic fractions are observed (based on chemical analyses), which is likely attributed to the entrainment of grains of ilmenite, titanomagnetite, olivine, and pyroxene containing fine apatite inclusions into the magnetic product.

Based on the results of magnetic analysis, laboratory investigations were carried out using magnetic separators.

In primary deposits of Ukraine, titanomagnetite is the productive mineral and predominates quantitatively; therefore, it can be recovered at the initial stage of the flowsheet using both dry and wet magnetic separation methods (Table 3).

Table 3 – Results of magnetic separation of the titanomagnetite fraction of the ore at a magnetic field intensity of 80–40 kA/m

Variant	Product	Yield, %	Mass fraction, %				Recovery, %			
			TiO_2	V_2O_5	Fe_{total}	P_2O_5	TiO_2	V_2O_5	Fe_{total}	P_2O_5
Wet	Titanomagnetite concentrate	13.6	22.3	0.51	53.1	0.51	49.2	80.7	34.97	2.51
	Non-magnetic product	86.4	3.64	0.02	15.5	3.11	50.8	19.3	65.03	97.49
	Feed material	100	6.18	0.09	20.6	2.76	100.	100.	100.0	100.0
Dry	Titanomagnetite concentrate	13.9	22.0	0.46	51.9	0.51	49.6	74.8	34.94	2.48
	Non-magnetic product	86.1	3.62	0.03	15.6	3.24	50.4	25.2	65.06	97.52
	Feed material	100	6.18	0.09	20.6	2.76	100.	100.	100.0	100.0

Under dry processing conditions, the ore was ground to a particle size of −0.25 + 0 mm and classified at a cut size of 0.04 mm. Analysis of the results of magnetic beneficiation (see Table 1) showed that the separation performance indicators is sufficiently high, irrespective of the separation medium.

As a result of this operation, titanomagnetite concentrate can be obtained from ore of - 0.25 mm + 0 mm size in an amount of 13.9% under dry magnetic separation, compared with 13.6% under wet beneficiation. The concentrates contains 22.0 – 22.3% of TiO_2, 51.9–53.1% of total iron, 0.46–0.51% of vanadium oxide, and 0.51% of phosphorus oxide.

In order to determine the value of the titanomagnetite concentrate, the chemical and mineralogical compositions of the strongly magnetic fraction (Table 4), recovered from primary ores by wet and dry magnetic separation in a field of 80 kA/m, were investigated.

The yield of the strongly magnetic fraction ranged from 13.6% to 13.9%. It contained 22.0–22.3% of TiO_2, 51.9–53.1% of total iron, 0.46–0.51% of vanadium oxide, 0.51% of phosphorus oxide, and up to 40% silica. It is shown that this fraction consists of 95.1–95.4% titanomagnetite, 0.1–0.2% ilmenite, 3.0–4.0% other minerals (olivine, pyroxene, sulphides, etc.), and 0.8–1.4% plagioclase and apatite.

Chemical analysis confirms the presence of vanadium oxide in ilmenite, which has undergone multiple stages of magnetic separation in a weak field (0.07–0.28%), indicating that vanadium is associated not only with titanomagnetite but also with ilmenite.

Studies of the material composition of ilmenite and titanomagnetite, as well as of olivine, has shown that ilmenite contains 0-0.1% vanadium, whereas titanomagnetite contains 0.2–1.9%, indicating that vanadium is present in significantly higher concentrations in titanomagnetite than in ilmenite.

Table 4 – Results of magnetic analysis of the strongly magnetic fraction

Magnetic field intensity, kA/m	Yield, %	Mass fraction of V_2O_5, %	Recovery of V_2O_5, %	Mineral grains and grain aggregates			
				Ilmenite	Titano-magnetite	Non-ore minerals	
						Dark-coloured minerals	Plagioclase
55	2.4	0.501	16.03	0.1	95.4	3.7	0.8
80	13.0	0.412	71.43	0.1	83.2	13.9	2.8
120	17.4	0.388	90.09	0.3	74.9	19.9	4.9
Non-magnetic product	82.6	0.009	9.91	4.8	0.1	58.3	36.8
Feed material	100	0.075	100.00	4.0	14.5	50.6	30.9

Two products were subjected to gravitational beneficiation: the non-magnetic fraction and the initial feed material.

The investigations were carried out in two stages:

– gravitational analysis of the products (to determine the distribution of minerals by specific gravity);

– beneficiation of the ore using laboratory equipment.

According to the results of gravitational separation, it is established that 98% of liberated ilmenite and titanomagnetite grains are recovered into the fraction with a density exceeding 4200 kg/m³. The fraction with a density of 4200–3400 kg/m³ is composed of 90–95% olivine and pyroxene.

The light fraction (less than 2800 kg/m³) is represented entirely by plagioclase grains (100%). The product with a density of 3600–2800 kg/m³ consists of a mixture of apatite, olivine, and pyroxene.

The investigations demonstrated that, in order to achieve maximum recovery of titanomagnetite, the non-magnetic product should be ground to a particle size of 0.2 mm.

Gravitational beneficiation of the products was performed using a shaking table. Table 5 presents the technological performance indicators of gravitational beneficiation of the feed material under optimal operating parameters of the shaking table. The table inclination angle was 7°, the deck stroke amplitude was 12 mm, and the solid mass fraction was 25%.

Table 5 – Results of beneficiation of raw material from a complex titanomagnetite deposit using a concentration table

Feed material	Product	Yield, %	Mass fraction, % of			Recovery, % of		
			TiO_2	P_2O_5	Fe_{total}	TiO_2	P_2O_5	Fe_{total}
Run-of-mine ore, deslimed at 0.044 mm	Titanomagnetite concentrate	17.70	24.1	0.56	36.0	58.6	3.47	30.86
	Olivine–pyroxene product	56.21	3.49	3.96	22.56	31.77	77.77	61.41
	Plagioclase product	19.80	1.13	2.07	1.50	3.62	14.30	1.44
	Slimes	6.29	5.9	2.03	20.65	6.01	4.46	6.29
	Feed material	100.0	6.18	2.86	20.65	100.0	100.0	100.0
Feed ore, size fraction 0.25+0 mm	Titanomagnetite concentrate	11.46	16.3	0.69	33.70	34.34	2.87	18.70
	Olivine–pyroxene product	47.75	7.96	4.04	32.77	27.72	69.83	75.77
	Plagioclase product	40.79	5.06	1.85	2.80	37.94	27.30	5.53
	Feed material	100.0	5.44	2.76	20.65	100	100	100
Non-magnetic product	Titanomagnetite concentrate	3.85	36.16	0.44	38.30	63.28	0.54	9.31
	Olivine–pyroxene product	51.65	1.27	4.71	23.36	23.51	78.30	76.17
	Plagioclase product	32.20	0.30	0.95	1.50	3.47	9.80	3.36
	Slimes	12.30	2.2	2.87	14.37	9.73	11.35	11.16
	Feed material	100.0	2.78	3.11	15.84	100	100	100

Products classified to a particle size of 0.044 mm are efficiently beneficiated on the shaking table (ε = 85.9% and 88.9%). From these products, titanomagnetite concentrates were obtained with yields of 17.7% and 3.85%, respectively, which were composed of titanomagnetite, ilmenite, olivine, and pyroxene.

The mass fraction of TiO_2 in the titanomagnetite concentrate obtained from ore of a complex deposit in Ukraine was 24.1%, whereas in the concentrate derived from the non-magnetic fraction it reached 36.16%.

Thus, as a result of gravitational beneficiation of products from complex titanomagnetite deposits, a titanomagnetite concentrate containing both titanomagnetite and ilmenite was obtained, along with a plagioclase product (tailings) with a yield of 19.8% and an olivine-pyroxene product with a yield of 56.21%. Further recovery of ilmenite can be achieved by electrostatic separation of the rough concentrate.

For the final recovery of titanomagnetite, the application of low-intensity magnetic separation after electrostatic separation is required. The investigations demonstrated that magnetic separation of these products enables the production of a titanomagnetite concentrate containing 97–98% of the valuable mineral. The mass fraction of V_2O_5 is 0.51%.

Based on the results of ore investigations conducted at Kryvyi Rih National University, as well as previously developed beneficiation flowsheets for apatite–ilmenite ores from certain Ukrainian deposits, a principal technological flowsheet for the beneficiation of ores from primary titanomagnetite deposits of Ukraine was developed.

The proposed flowsheet involves the recovery of a vanadium-bearing concentrate at the initial stage by magnetic separation (Fig. 2).

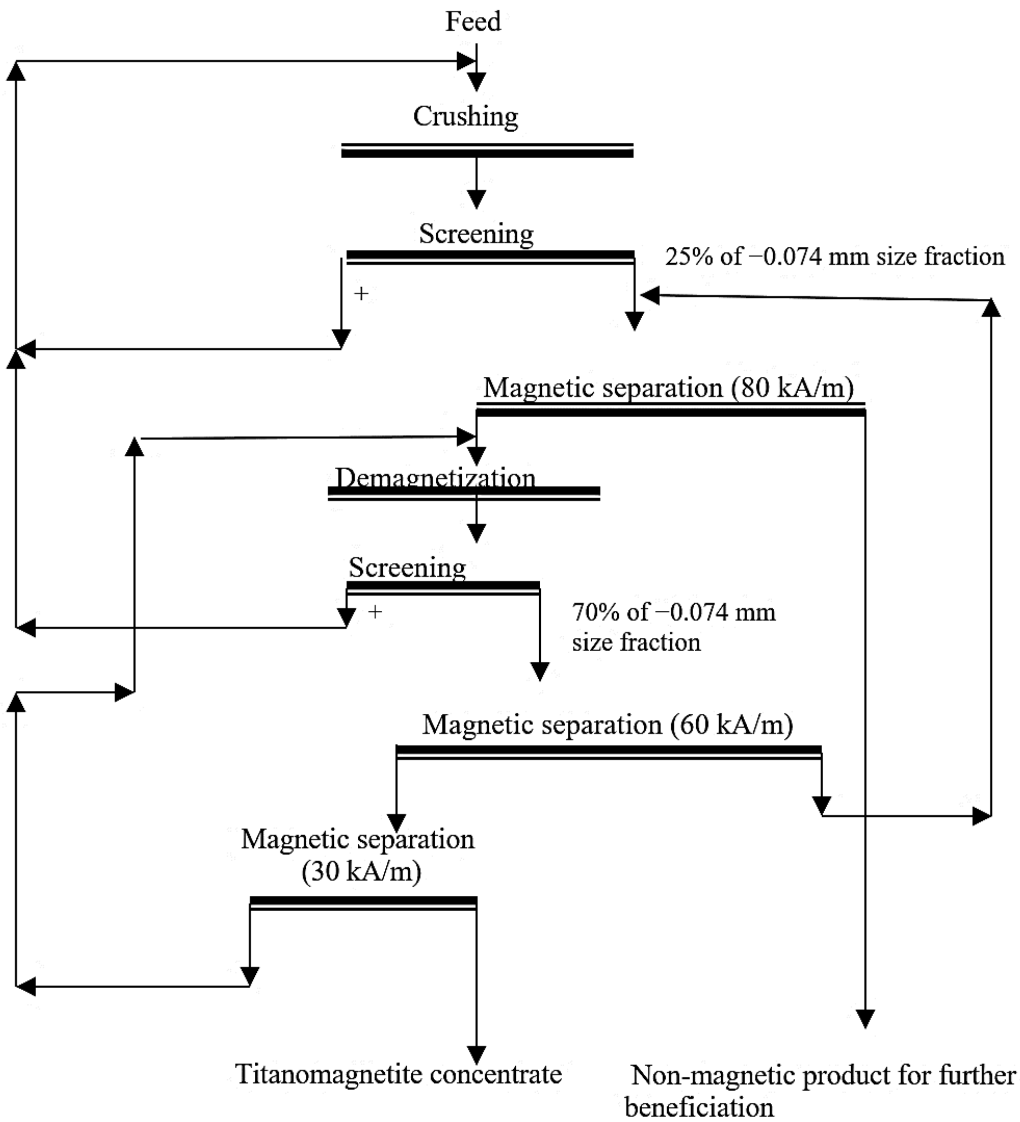


Figure 2 – Flowsheet of titanomagnetite ore processing including crushing, screening, staged magnetic separation, and demagnetization

In the proposed flowsheet, the raw material was ground in a single stage to achieve 25% of the - 0.074 mm size fraction in an air-swept mill operating in a closed circuit with air classification in an air separator. A screening unit is installed to control the particle size of the material.

It is assumed that vanadium-bearing concentrate is produced by a dry method using low-intensity magnetic separation, after which the non-magnetic fraction is fed to gravitational beneficiation.

Dry low-intensity magnetic separation of the crushed ore enables the solution of two tasks: recovery of a vanadium-bearing concentrate at the initial stage of the process, consisting of strongly magnetic titanium-bearing minerals, and reduction of the material volume to be subjected to drying at the final stage of the technological flowsheet.

The proposed flowsheet has the following advantages:

– increased recovery of titanomagnetite minerals into the vanadium-bearing concentrate, as it is recovered at the initial stage of the process;

– a 20% reduction in the load on the equipment employed in the flowsheet;

– reduced formation of fine fractions, as crushing is performed in a single stage;

– water consumption is reduced by 20%.

A flowsheet for processing titanomagnetite concentrate for the recovery of vanadium is presented in Fig. 3.

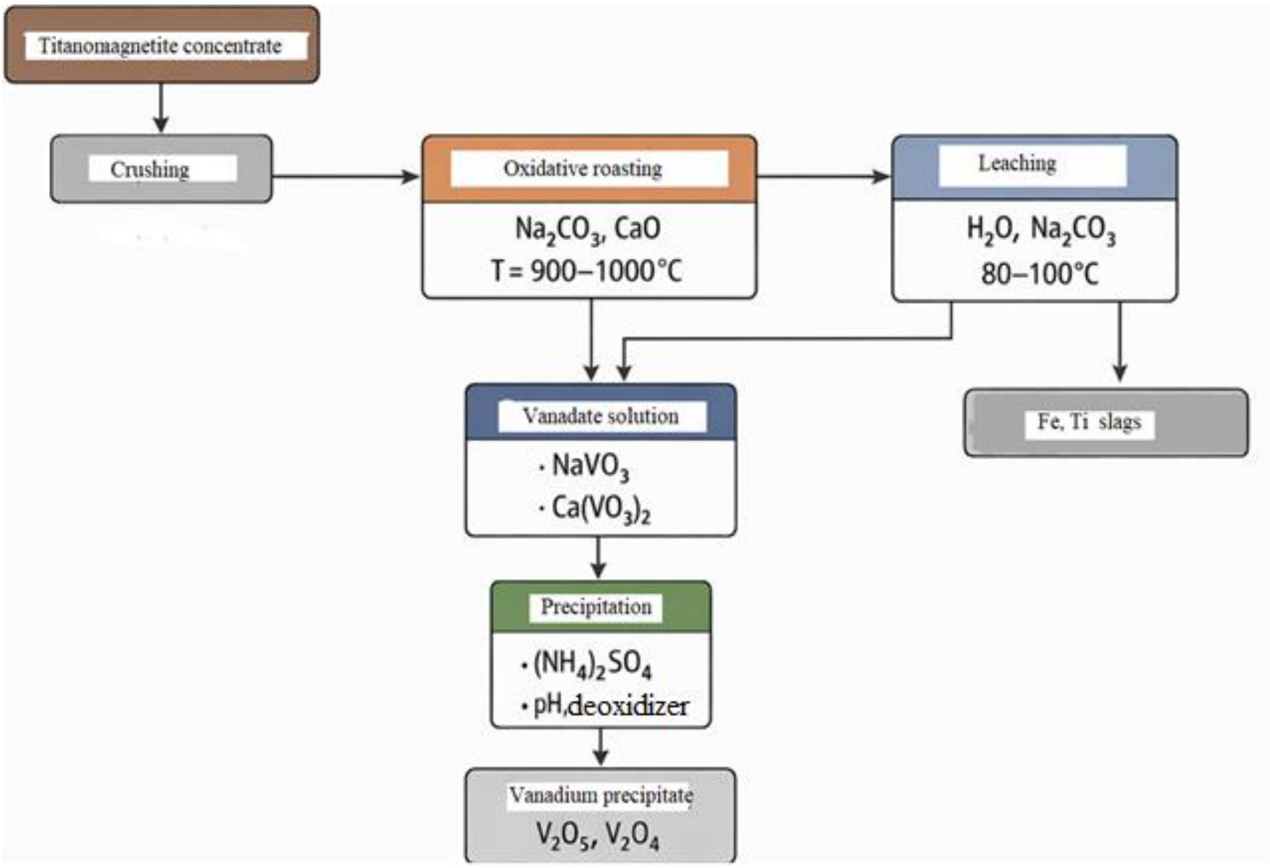


Figure 3 – Scheme of processing of titanomagnetite concentrate for the extraction of vanadium

After vanadium recovery, the application of a combined technology for iron and titanium separation is considered appropriate, which is based on reductive smelting with the transfer of iron into the metallic phase and concentration of titanium in the slag product, followed by hydrometallurgical or chloride processing (Fig. 4).

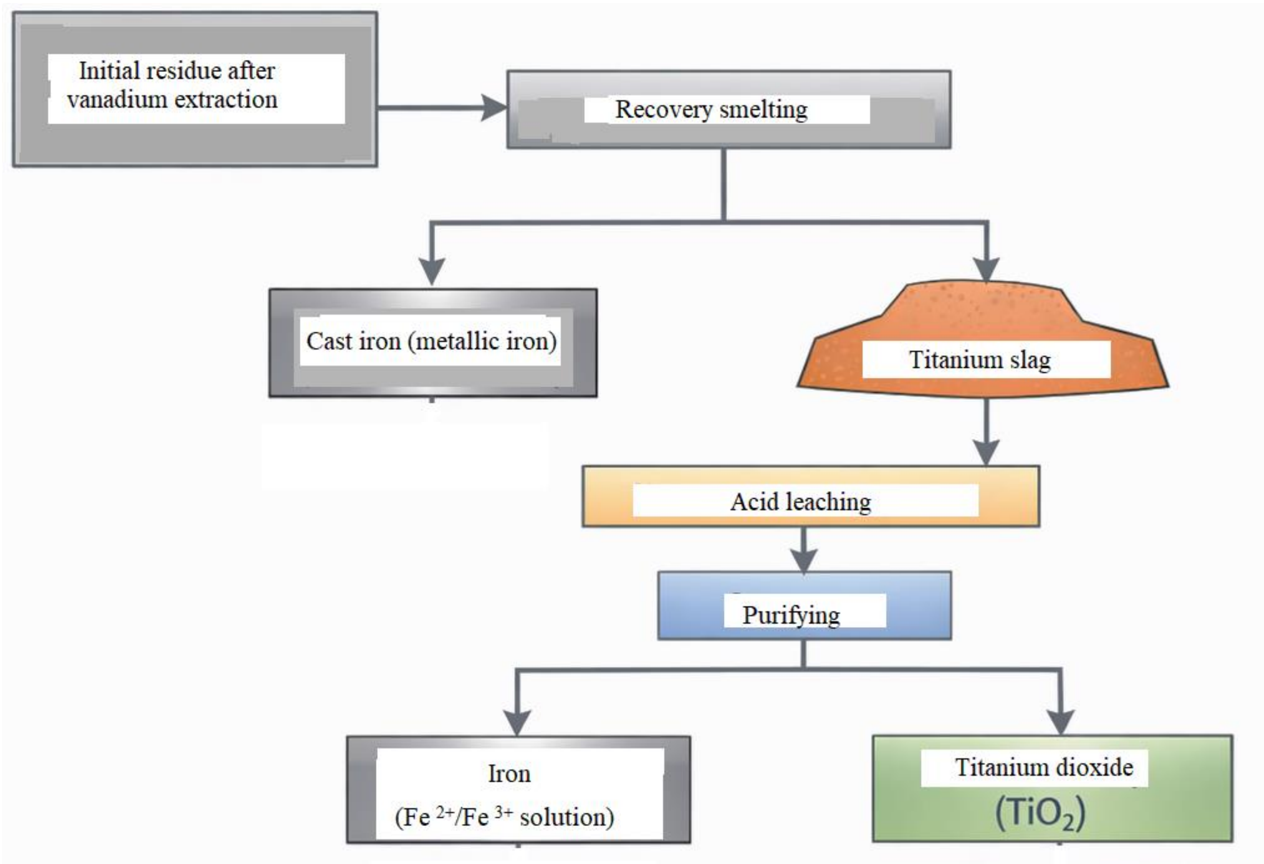


Figure 4 – Schematic diagram of the separation of iron and titanium after vanadium extraction

Such an approach ensures high process selectivity, comprehensive utilisation of raw material components, and compliance with modern requirements of resource efficiency.

4. Conclusions

For the first time, it is established that primary titanomagnetite ores of Ukraine are characterised by complex mineral structure, with predominant localisation of vanadium in titanomagnetite (up to 1.9%).

It is proven that grinding to −0.074 mm was required for complete liberation of ore minerals.

The understanding of magnetic separation of titanomagnetite ores is improved. In particular, it is established that an increase in magnetic field intensity is accompanied by increased recovery not only of ore minerals but also of silicate minerals, which determines the selectivity limits of the process.

For the first time, the feasibility of recovering a vanadium-bearing concentrate at the initial stage of the technological flowsheet is substantiated, allowing modification of the conventional processing logic (from “final recovery” to “recovery at the head of the process”).

An approach to combined magnetic–gravitational beneficiation is further developed, taking into account the degree of mineral liberation and their physicochemical properties, thereby ensuring enhanced comprehensive utilisation of raw materials.

It is established that dry and wet magnetic separation provided comparable technological performance indicators: concentrate yield of 13.6%–13.9% with TiO_2 content up to 22.3% and V_2O_5 content up to 0.51%.

The efficiency of gravitational beneficiation is demonstrated, which enables a further increase in titanium content in the concentrate up to 24.1% –36.16%.

A combined magnetic–gravitational–electrical beneficiation technology is developed, which ensures the production of concentrate containing up to 97%–98% titanomagnetite.

The proposed technological flowsheet enables the production of vanadium-bearing titanomagnetite concentrate with V_2O_5 content up to 0.51% and ensures a high degree of recovery of iron (up to 80%) and titanium into the concentrate.

Implementation of concentrate recovery at the initial stage of the process provides a reduction in the load on subsequent operations by up to 20% and a decrease in the volume of material subjected to drying and fine grinding, thereby reducing overall energy consumption.

The proposed flowsheet ensures a reduction in water consumption by up to 20%, which is critically important under modern production conditions and is consistent with the principles of the circular economy.

The obtained results make possible to:

– form a vanadium raw material base in Ukraine;

– expand the product range through comprehensive utilisation of the ore (Fe-Ti-V-P*)*;

– improve the economic efficiency of deposit development.

The technology can be directly applied in the design of new beneficiation plants, the modernisation of existing facilities, and the preparation of feasibility studies for titanomagnetite ore deposits.

The proposed approach creates prerequisites for further processing of the concentrate using pyrometallurgical methods (reductive smelting) and hydrometallurgical technologies for vanadium recovery.

Conflict of interest

Authors state no conflict of interest.

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КОМПЛЕКСНЕ ЗБАГАЧЕННЯ КОРІННИХ ТИТАНОМАГНЕТИТОВИХ РУД УКРАЇНИ З ОТРИМАННЯМ ВАНАДІЙВМІСНОГО КОНЦЕНТРАТУ

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Анотація. У роботі досліджено речовинний склад, технологічні властивості та можливості комплексного використання корінних титаномагнетитових руд України з метою отримання ванадійвмісного концентрату.

Дослідження проводилися в лабораторних умовах за стандартними методиками із застосуванням магнітних сепараторів роликового типу 138Т-СЕМ і роторного типу 259-СЕ; концентраційного столу СКМ-2.

В процесі досліджень вивчались речовинний склад та технологічні властивості руди, на підставі чого розроблялася технологічна схема збагачення.

Встановлено, що основними рудними мінералами є титаномагнетит (13,5%), ільменіт (≈5 %), апатит (6,08%), тоді як породоутворююча частина представлена плагіоклазами, піроксенами та олівіном. Ванадій переважно ізоморфно входить до структури титаномагнетиту, що ускладнює його вилучення.

У роботі вперше для корінних титаномагнетитових руд України обґрунтовано доцільність вилучення ванадійвмісного концентрату на початковій стадії збагачення, що дозволяє підвищити селективність процесу та знизити ресурсні витрати. Розвинуто наукові підходи до комбінованого магнітно-гравітаційного збагачення з урахуванням ступеня розкриття мінералів і їх фізичних властивостей.

На основі мінералогічних і гранулометричних досліджень встановлено, що повне розкриття рудних мінералів досягається при подрібненні до класу –0,074 мм. Магнітний аналіз показав, що титаномагнетит ефективно вилучається у широкому діапазоні напруженості магнітного поля, однак із підвищенням інтенсивності зростає захоплення супутніх силікатів.

Експериментально підтверджено ефективність як сухої, так і мокрої магнітної сепарації. Отримано титаномагнетитовий концентрат із виходом 13,6–13,9% та вмістом TiO_2 22,0–22,3%, Fe – до 53,1% і V_2O_5 – до 0,51%. Подальше гравітаційне збагачення дозволяє підвищити вміст TiO_2 до 24,1–36,16% залежно від типу живлення.

Практична значущість роботи полягає у розробці ефективної технологічної схеми, яка забезпечує комплексне використання сировини, зниження водо- та енерговитрат, а також може бути впроваджена при проєктуванні збагачувальних підприємств і формуванні сировинної бази титану, заліза та ванадію в Україні.

Ключові слова: титаномагнетитові руди; комплексне збагачення; ванадій; технологічна схема